A METHODOLOGY FOR AUTOMATION AND ROBOTICS EVALUATION APPLIED TO THE SPACE STATION TELEROBOTIC SERVICER

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ABSTRACT

The efforts of a recent study aimed at identifying key issues and trade-offs associated with using a Flight Telerobotic Services (FTS) to aid in Space Station assembly-phase tasks is described. The use of automation and robotic (A&R) technologies for large space systems would involve a substitution of automation capabilities for human EVA or IVA activities. A methodology is presented that incorporates assessment of candidate assembly-phase tasks, telerobotic performance capabilities, development costs, and effects of operational constraints (STS, attached payload, and proximity operations). Changes in the region of cost-effectiveness are examined under a variety of system design assumptions.

A discussion of issues is presented with focus on three roles the FTS might serve: (1) as a research-oriented testbed to learn more about space usage of telerobotics; (2) as a research based testbed having an experimental demonstration orientation with limited assembly and servicing applications; or (3) as an operational system to augment EVA and to aid the construction of the Space Station and to reduce the programmatic (schedule) risk by increasing the flexibility of mission operations.

INTRODUCTION

There has been continuing interest in the use of telerobotics for Space Station activities as a possible means for reducing EVA/IVA activities and operations costs, increasing safety, and improving the technology base and spin-off potential of telerobotics (NASA/JSC, January 15, 1987; National Academy of Sciences, 1986). A large-scale analysis of the Space Station assembly phase by the Critical Evaluation Task Force (CETF, 1986) in the Fall of 1986 resulted in the concern that the required EVA hours for assembly exceeded on-orbit EVA time constraints. This concern resulted in the recommendation that a Flight Telerobot Servicer (FTS) be used as an option for possible use starting at First Element Launch (FEL--the first flight in the Space Station construction phase). While the CETF recognized that an FTS could make a substantial contribution to reducing EVA during the construction phase, it was not clear whether such a system built with an inherent technical risk would be cost-effective. This question motivated the need for the methodology presented herein.

A key milestone for Space Station assembly, the Permanently Manned Configuration (PMC), is the point at which astronauts can reside for long periods on orbit without returning to earth with the Space Shuttle. The period from FEL to PMC is severely constrained for EVA resources, due to the short (Shuttle-based) time intervals for construction (approximately one week). There is a need to displace EVA resources; where "need" is defined as an FTS capability to reduce crew-EVA time so that absolute Shuttle-based EVA limits are not exceeded. Furthermore, the FTS must accomplish this reduction in a manner that is at least as cost-effective and reliable as available alternatives. The degree of mismatch between task activities and EVA requirements during the construction phase results in excessive EVA (which is expensive and hazardous), additional power requirements for the Space Station (to support the additional crew to perform the EVA tasks), and potential additional STS flights to "make up" shortages of EVA time. After PMC, the value of the FTS can be argued to depend on a more complex set of considerations: life-cycle cost, productivity gains, safety improvements, technology spin-offs, and other factors. This paper focuses on cost factors: considerations such as safety and technology spin-off benefits were not explicitly addressed.

The purpose of this paper is to present an approach for assessing the feasibility of utilizing telerobotic systems in the space environment and present the results of an application of the methodology to the Space Station. The results and design issues encountered are based on a recent investigation by the authors (Smith, et al., 1987).

APPROACH FOR COMPARING SPACE STATION TELEROBOTICS OPTIONS

A comparison of Space Station telerobotics options involves many complex factors. The objective is to provide a systems-level methodology that addresses the important components affecting the value of an FTS to the assembly phase. The approach, illustrated in Figure 1, is delineated below.

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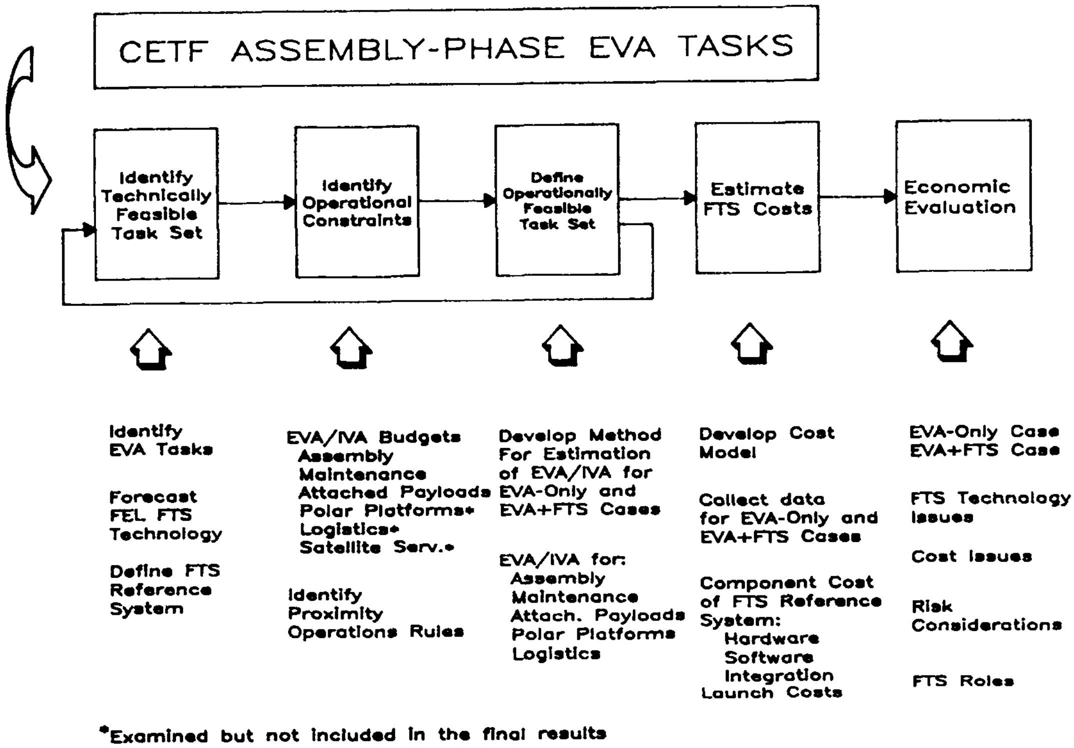

Figure 1. FTS Assembly Phase Study Approach

Technically Feasible Task Set

A technically feasible task set is derived from a list of task activities (based on CETF, contractor studies, etc.) in the areas of assembly, payload servicing, and maintenance. In parallel, an FTS "Reference System" is defined based on a review of potential technologies required to implement the tasks, and, that will be available by FEL (i.e., 1996). For the Space Station application, an FTS Reference System is derived that could perform a subset of the assembly phase tasks at a level of technical readiness corresponding to the FEL date (although the technically feasible task set and corresponding Reference System may initially be somewhat incompatible with total system constraints). However, the purpose of this step is to capture the possible extent of task requirements and capabilities before applying operational constraints to insure the final reference configuration functionality is synchronized with all system constraints.

Operational Constraints

The operational constraints consist of EVA and IVA budgets and proximity operations rules that reduce the technically feasible task set to an operationally feasible task set. The following categories of activities were examined to estimate the EVA and IVA times for two cases: EVA-Only (no FTS) and EVA+FTS (FTS present) (NASA/JSC: March 1986; November 1986; January 8, 1987).

(1) Assembly tasks
(2) Maintenance tasks
(3) Attached payload setup and servicing tasks

The operational constraints are overlaid on the technically feasible tasks set to derive an operationally feasible task set, and the FTS Reference System definition is revised to reflect the operational constraints. The EVA and IVA times for the two cases were estimated by flight, category (assembly, maintenance, and attached payloads), and year during the construction phase to measure the savings accrued by the FTS during the operations phase (Machell, 1986, McDonnell-Douglas, 1986).

Flight Telerobotic Servicer (FTS) Reference System

To assess the benefits and costs of an FTS, a design concept is required to focus the required technology capabilities and estimate costs. An FTS system is needed that is appropriate for specific EVA tasks required for assembly and operation of the Space Station between FEL and IOC. Such an FTS forecast addresses the availability of critical constituent technologies required at FEL, and highlights essential support characteristics such as FTS reliability, maintenance, and associated logistics support. Selection of technology capabilities must also consider schedule requirements (when must the system be operational), technology and system integration, system verification and testing, and system integration into Space Station operations. The study objective was to identify a low-risk, technically feasible FTS

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Reference System that could be ready by FEL and could perform a set of operationally feasible tasks during the Space Station construction phase.

Before developing a reference configuration, the functional requirements for the system as a whole must be understood (NASA/JPL, 1986). As the desired functional capabilities are explored, obvious conflicts between FEL functions and technologies are identified and used as discriminators to maintain the list of functional requirements within the realm of feasibility (e.g., tasks requiring a considerable amount of on-line planning for fault management, or a large degree of dexterous manipulation, would not have the commensurate technology in place to meet the task needs). Tasks considered technically feasible in the FEL to IOC time frame include (1) basic assembly tasks such as pallet handling, worksite preparation, or truss construction in a well-defined, almost industrial robotic type environment, (2) simple orbital replaceable unit (ORU) change-out and inspection type tasks on payloads, (3) Space Station support tasks such as surface cleaning and inspection, (4) pick-and-place type logistic tasks such as transferring components or fluid consumables from the Shuttle to the Station, and (5) other support such as transporting equipment from one place to another, holding equipment in place while it is worked on by EVA astronauts, or providing on-site visual monitoring of an EVA task.

Given a set of possible technically feasible tasks, telerobot technologies are matched against those tasks. The key variables in selecting the technologies are:

(1) Level of technology readiness (i.e., with FEL being the deadline for delivery)
(2) Degree of system integration
(3) Accuracy and repeatability requirements
(4) Reliability
(5) Retrofit considerations for future capabilities growth

An important element of technology readiness is whether the technology has the potential for being flight-qualified by FEL (Zimmerman and Marzwell, 1985). Empirical data gathered on system development elapsed time from concept to full operational capability (i.e., space qualification) suggest a time frame between five and ten years for moderately complex systems, and ten to twenty years for complex systems. Therefore, considering the FTS system as a moderate-to-complex design with an appropriate logistics support program in place by FEL, it was determined that likely FTS robotic technologies would probably not exceed the present state-of-the-art unless an aggressively funded flight test program or other experience gathering mechanism were introduced to reduce risk.

The next stop in identifying a reference system is to develop an array of "strawman" FTS configurations that contain the required robotic technologies while meeting the projected task requirements. It was understood that the same tasks could be done in different ways, depending on the FTS configuration. For example, employing a more sophisticated configuration such as a mobile FTS versus a fixed FTS offers greater flexibility and a wider range of applicability in component handling types of tasks. By developing several strawman configurations, it is possible to understand how other factors such as operational constraints (e.g., FTS operations in proximity to EVA) might influence the selection of particular configuration over another. It is likely that EVA-FTS proximity operations constraints could severely limit the possibility of any type of free-flying FTS being deployed. System control constraints imposed by the task environment and available technology could also limit the ability of the system to compensate for self-induced or environmentally induced dynamic disturbances or changes in the pre-planned task environment. For control and vision purposes, the approach is to select the most reasonable reference configuration from the subset of strawman designs. This study, supporting an FEL in the early 1990's, resulted in a reference design having a fixed base in which the fixed base is fastened and the FTS is transported manually to the base using the Shuttle RMS or the MSC where it is connected for operations.

Assembly Phase EVA and IVA Resource Estimates

Due to large uncertainties in some of the data components, ranges are used to bound the results (a formal analysis of these uncertainties was not performed). The total EVA times per flight-interval for the EVA-Only and EVA+FTS cases are illustrated in Figure 2 using low-range EVA estimates for construction, maintenance, and attached payloads. The low-range values represent the lowest estimates for the EVA range obtained by adding all the low values together. A similar procedure was used for the high-range estimates. The aim was to bound the actual values by examining the extreme low and high values. The estimates of Figure 2 are troubling. The estimated EVA required on five flights prior to PMC exceeds the budgeted amounts of 24 hours. This finding supports the argument that the CETF assembly sequence does not manifest within the CETF constraints for at least three early flights. This is due primarily to construction on Flights 1 and 2 and maintenance and attached payload contributions on subsequent flights. The implication is that for the CETF design to work, one or more shuttle flights must be added, the current shuttle flights must be extended (unlikely), or there must be a re-manifesting of construction EVA to meet the constraints. It is the cost of additional shuttle flights that dominates the cost-effectiveness of the FTS.

RESULTS: ASSEMBLY PHASE COMPARISON WITH AND WITHOUT THE FTS

An economic model was developed to examine the cost-effectiveness of the FTS Reference System and to determine whether the FTS could be cost-effective during the construction phase. The Net Savings model is:

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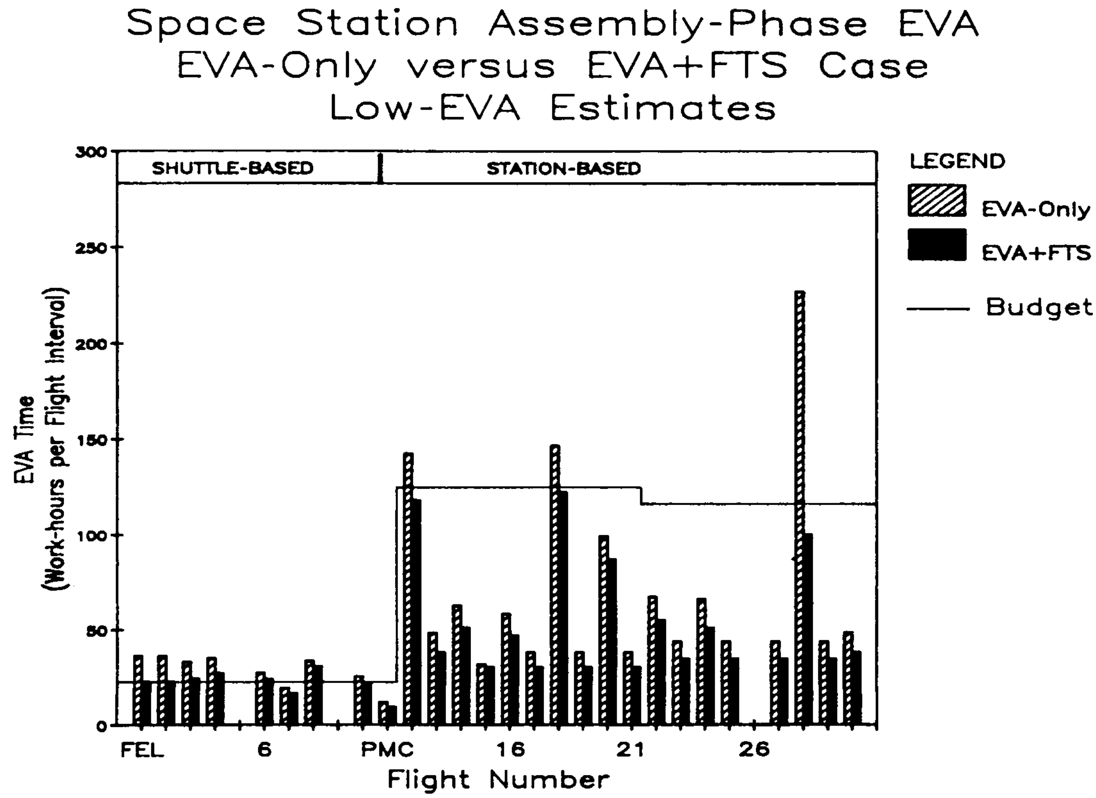

Figure 2. Construction Phase EVA Estimates--Low-Range EVA Values

Net Savings Due to the FTS Reference System = (Operations and Maintenance Cost of EVA-Only Case minus
Operations and Maintenance Cost of EVA+FTS Case) minus
Investment Cost of the FTS.

If the Net Savings is positive, the FTS Reference System is cost-effective. The use of this approach required a cost estimate of the FTS Reference System and a bottom-up cost (component-by-component) estimate was made using the component list for the FTS Reference System (Smith, et.al., 1987). An estimate of $277 million (M) to $304 M was obtained for the FTS (excluding non-prime costs--the costs of managing the prime contracts and spares costs). The costs and benefits for the development of the FTS up to the completion of the construction phase were examined. At issue was the feasibility of using the FTS to assist in the assembly process. Thus, benefits to users or the Station after the construction phase were not examined. FTS ground operations costs were included using estimates of FTS operating costs. Using these cost estimates and the EVA and IVA profiles, a series of analyses were performed to determine the feasible region for the FTS Reference System.

The results indicate that during the assembly phase the major tradeoff evolves around the cost of the FTS and the cost-per-flight of the STS. Because of cases where the estimated EVA exceeds the budget of 24 hours during FEL to PMC, additional flights must be added to make up the difference. The cost of any added flights as a major factor in the cost-effectiveness of the FTS. Figure 3 presents one such trade-off region using the low-range estimates of EVA/IVA and the FTS cost over a range of STS costs per flight from $105M to $178M. It is difficult to determine an estimate for STS prices. Estimates have ranged from below $100M to $150M during the pre-Challenger era. The assumption was made that the price will be higher in the post-Challenger era due to increased safety and reliability requirements, component re-designs, and quality control constraints. However, a range of price curves is presented to provide a generalized result. The FTS cost ranges from a low $232M (NASA estimate) to $340M (National Research Council, 1987); the end points were selected merely to bound the trade-off region. The area in the center of the region bounds the FTS Reference System estimated costs. As an example, if we assume a STS cost of $150M, the FTS will break even if it can be built for a cost of $292M or less. If the FTS costs more than $292M, it will not be cost-effective (unless the STS price is actually higher). For the other points on any of these curves, the estimated net savings can be read from the axis on the left.

Also, note the term "Mixed Manifesting" on Figure 3. This refers to assumptions made regarding how

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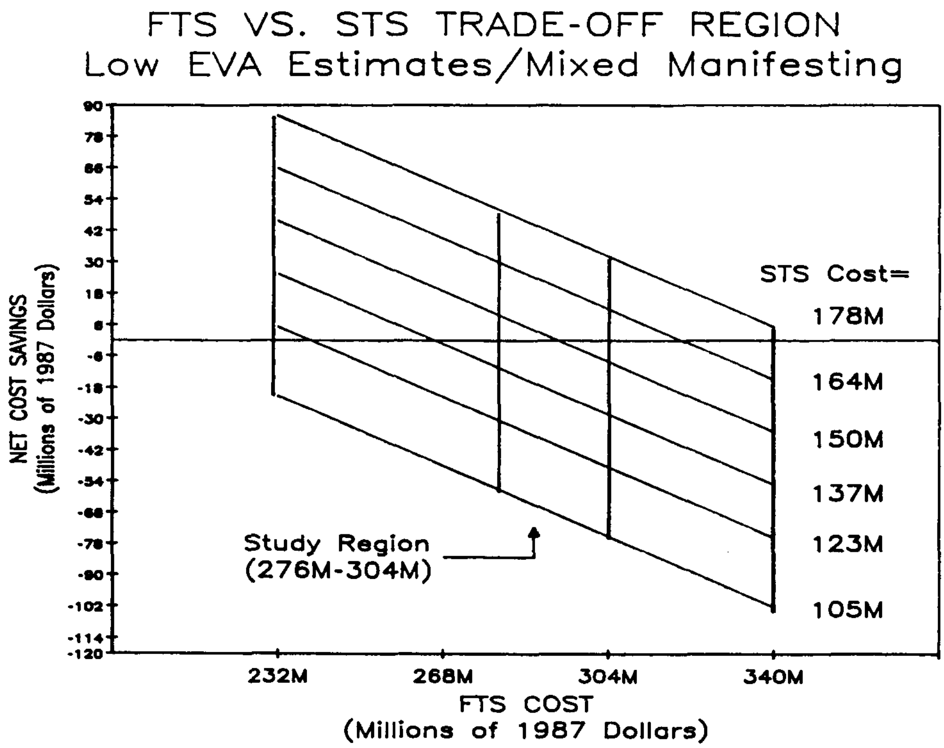

Figure 3. FTS versus STS Trade-Off Region

excess EVA is remanifested on subsequent flights if an additional flight is required. Note that as manifesting becomes inflexible, the FTS cost effectiveness region moves up (toward cost-effective) and as manifesting becomes flexible, the FTS cost-effectiveness moves down (toward less cost-effective).

If the scenario is moved toward the flexible manifesting assumption, the trade-off region moves down (toward less cost-effective) because fewer overall flights are required. If the scenario is moved toward the inflexible manifesting assumption, the region moves up (more STS flights are required). Furthermore, as the differences between the number of additional flights in the EVA-Only case and the EVA+FTS cases (if any) becomes larger, the width or spacing between the curves also becomes larger. The constant slope of the curves (approximately -0.75) is an indication that for each reduction in FTS cost of one dollar, there is an increase in net savings of only $0.75. The remaining 25% is the delivery cost and the effects of discounting.

The region in Figure 3 is for the low-range EVA values. If the high-range EVA values are used, the region moves down. Similarly, as the estimated cost of the FTS increases, cost-effectiveness drops (the region shifts downward).

Another parameter of interest is the EVA cost per hour used to estimate the cost of EVA hours used. As with the STS cost, the estimation of such a value is difficult. To examine the sensitivity of the results to EVA cost per hour, three cases were examined using $45,000 ($45K), $35K, and $25K per hour. Note the apparent insensitivity of the region to this parameter. This is due to the magnitudes of the numbers between the FTS and STS costs. A decrease in the cost per hour simply places less value on the resource benefits the FTS can displace and thus makes the FTS region move down. At least for the assembly phase, it appears that EVA cost (summed over a reasonably short period of time) are dominated by the Shuttle ferrying costs. This result does not imply that <u>life cycle</u> Space Station EVA costs will be equally insignificant. The discount rate used in the above results is the Office of Management and Budget (OMB) value of 10% used for cost-benefit analysis on government projects. The effect of varying the discount rate was also examined using a 6% rate. The effect of reducing the discount rate is to move the trade-off region up significantly. This indicates that a lower discount rate would have a significant impact on improving the cost-effectiveness of the FTS.

DESIGN ISSUES AND IMPLICATIONS

A key deisgn issue is to identify the key attributes of the FTS program that affect the trade-offs to be made between the numerous users the robotic system faces. If the attribute to be maximized is the commercial benefit to be derived from technology advances (i.e., spin-off potential), then a different value equation (than net savings) will need to be constructed in order to accommodate these technologies to be stimulated, and thus the activities that the FTS can be used to demonstrate. It was assumed here that the objective was to maximize the overall value of the FTS to the Station. Thus, technology development programs need to be instituted that enable FTS performance upgrades in areas that directly enhance FTS value to the Station. This could be done by identifying high-payoff applications amenable to acceptable-risk FTS system configurations. This assumption need not minimize the role of the FTS program in stimulating automation and robotic (A&R) technology development since both terrestrial spin-off and Station benefits can accrue from development of intelligently selected advanced technologies.

The current study was performed over a period of time in which the Station design moved from the CETF concept to an abbreviated Phase I configuration. However, because the STS-based EVA activity is still highly constrained in the Phase I case, the results are likely to be robust.

It is important to note that whether or not the FTS is cost-effective for the assembly phase, there are still legitimate uses under a number of scenarios. If the FTS is not cost-effective, it could still serve as a research and development testbed for post-IOC applications. If it is cost-effective, it could be used as an applications-oriented tool. Earlier studies have highlighted some of these role differences varying from a low-cost orbiter-based operational system to a space-based testbed for evolving telerobotics technologies (Goddard, 1986). Although there is a range between an applications-oriented versus a demonstration-oriented FTS, even if marginally cost-effective, the FTS could still serve as a backup, that could reduce schedule risks by providing a flexible assembly/servicing option for some additional EVA activity, if needed. This is an important design issue because it must be shown that a net risk reduction exists. Situations where the added risk of a large robot system (that could fail into a dangerous mode, or require extensive maintenance or EVA attention) must be understood prior to dedication of the system to an operational role. A robotic system can play a testbed or demonstration role in order to gather experience with on-orbit operations at a point where the design of the operational system can be modified. The interfaces between the human operators, the equipment, and the task requirements can be refined or revised to make better use of the synergistic potential of re-designed tasks coupled with FTS capabilities specifically designed for those tasks. If it is assumed that FTS operations are terminated at IOC, or that the FTS is not used for Station operations but rather for research and demonstration purposes, then there are other benefits this paper made no attempt to qualify. One class of benefits is the development of "lessons learned" that can be utilized to develop a future FTS that does play an integral role in a wider variety of Station and on-orbit operations. Such experience would provide a valuable database for guiding the design of future tasks and FTS capabilities.

Note that the analysis performed herein is inherently conservative. Limiting the time frame of the analysis to the construction phase underestimates the actual benefits of an FTS by excluding any post-IOC benefits. If the FTS is assumed to continue operations after IOC, the FTS feasibility region will tend to move upward (towards more feasible) for all cases. This paper presents a single solution out of many possible ones, and the results described are by no means optimal. The FTS option selected here was based on an analysis of estimated task requirements and estimated functional requirements. The focus was to identify the components that ought to be examined when comparing FTS options. Nonetheless, a number of recommendations are made.

There is a need to examine the effects of risk in these comparisons (Smith, et al., 1985). Cost risk can be viewed directly using the net savings, or operations and maintenance (O&M), equations to generate breakeven estimates for net savings and O&M costs. Then, as assumptions of the problem (such as software/integration costs) are varied, the impact on the breakeven point can be computed. Technical risk can also be studied in terms of the uncertainties in performance and reliability. In addition, the effects of specific risk elements, such as the effects of introducing suits requiring no pre-breathe step, EVA overhead, and the effects on EVA if such a suit is not ready on schedule, could be singled out. An understanding of the risk and uncertainty effects would show how the FTS could help reduce program risk by adding flexibility to operations planning and contingency planning--especially during FEL-PMC. There is value and benefit of having an FTS for the flexibility it provides for dealing with unscheduled events. Further study of the risk elements would quantify those benefits.

Additional study is also needed for the allocation of automation and robotic functions. Very different results can be achieved by locating such functions on the ground. With improved autonomous operations, Station IVA could be reduced. One question is whether to puruse advanced and potentially technically risky autonomous or semi-autonomous options versus an investment in on-the-ground remote telerobot operation capability. Such activity would identify the issues related to the human factors and control technology problems of dealing with time delays in teleoperation feedback. It may be possible to mitigate the problems of such time delays with predictive control and large scale dynamic task environment simulation technologies. The present paper has shown the magnitudes of the savings to be potentially large enough that a dedicated FTS relay system to provide near real-time response might be an alternative worth considering. This will depend on the potential for extending the displacement of IVA and EVA task times while minimizing the technical risk of developing the system. If extended operations can be performed from the ground, the risk of requiring additional flights may be reduced and provide a schedule margin during the early FEL-PMC period when assembly elements must be completed within fixed, short term flight periods or risk mission failure. The area of allocation of autonomous and robotic functions and resources needs further examination to help designers select whether A&R upgrades are performed on the Station, incorporated into the FTS, or operated on the ground (see Zimmerman, et al., 1985).

A related allocation problem that requires further understanding is the allocation of work among and between multiple robots (FTS, RMS, MSC, etc.) and crew EVA (co-EVA). Data on performance time ratios for such mixed tasks should be collected for a variety of tasks using neutral bouyancy studies and (eventually) on-orbit experience. The proximity operations rules for such operations will also have to be identified in detail.

DISCUSSION AND CONCLUSIONS

A number of conclusions can be drawn, based on a CETF-derived (30-flight) construction phase. Noting that the results are conservative in that benefits were not considered; safety benefits were not considered; and the effects of the satellite servicing facility were not examined; the following conclusions were drawn:

(1) The FTS Reference System identified herein appears to be technically feasible for development by FEL.
(2) The FTS Reference System is cost-effective under a variety of conservative scenarios.
(3) The STS cost is the primary factor for FTS cost effectiveness due to avoidance of extra STS flights, driven by EVA reductions.
(4) The FTS is cost-effective at a 10% OMB discount rate but even more cost-effective at a 6% rate.
(5) The assembly-phase is a maintenance problem (50% of total EVA is for maintenance versus 33% for construction). FEL-PMC is the primary construction problem.
(6) The FTS Reference System defined here is most suitable for performing:
   (a) Truss construction tasks
   (b) Limited ORU replacement tasks
   (c) Deployment of special equipment
   (d) Pallet handling, loading, and unloading tasks

   The potential exists for transferring some on-orbit tasks to ground operations given that appropriate technology and human engineering constraints are considered.
(7) The total estimated cost of the FTS Reference System is $277 to $304M (does not include non-prime costs or spares).
(8) There is a need for improved and more detailed data on task descriptions, timeliness, manifests, etc. updated quarterly or semi-annually and available via electronic mail, for example.
(9) A methodology for comparing automated and robotic options has been developed with specific applications to the FTS and its technical and cost feasibility for use during construction phase construction. Other A&R elements could be analyzed in a similar manner (see Zimmerman, Bard, Feinberg, 1985).

The approach described in this paper is intended to assist in the characterization of an assembly role for which an early robot or FTS might best be designed. Potential for cost-effective early operation argues for an FTS and host environment designed to facilitate performance of the selected FTS tasks. On the other hand, marginal early operating benefits suggest the option of treating the FTS initially as a testbed for development of advanced technologies that will later serve the Station in a more cost-effective manner.

A related issue is that of reliability, or more accurately, program confidence in the reliability of the FTS to perform tasks determined analytically to be cost-effective. The Advanced Technology Advisory Committee and Space Station work package contractors have been remarkably consistent in their conclusions regarding which tasks were within the capabilities of telerobotic devices. Program personnel, citing the criticality of early (pre-PMC) EVA tasks, are considerably more skeptical. The CETF, for example, ultimately based its results on the use of deployable utilities in preference to use of an FTS, on the grounds that on-orbit construction by telerobotic devices had never been attempted. This suggests that the subject of both ground and flight demonstrations of the FTS should be directed specifically toward whatever tasks the FTS might be applied to initially, particularly in cases of high task criticality.

Finally, multiple competing goals have been articulated for the mandated FTS development program and it is not clear that the program adequately addresses this issue. For example, the goal of increased Station productivity and decreased operational cost implies a high-reliability, low-technical risk, low-maintenance FTS that can be brought on-line early in the Station operating life. This approach cannot be easily reconciled with the aggressive station/FTS program schedule and less aggressive investment in A&R technology development. At the same time, it is clear from studies such as the CETF, that the "push-in here-pop-up there" EVA manifesting problem will not go away in the immediate future.

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